X(3872) Studies in LHC Run 3

Novel probes of the Quark-Gluon Plasma medium

LIP Summer Internship 2025 Final Workshop

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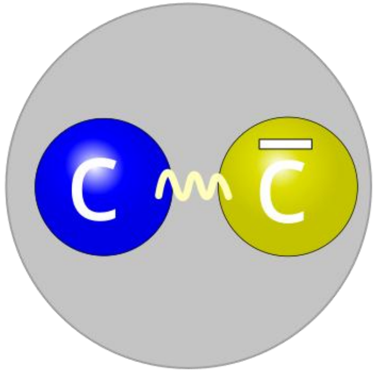
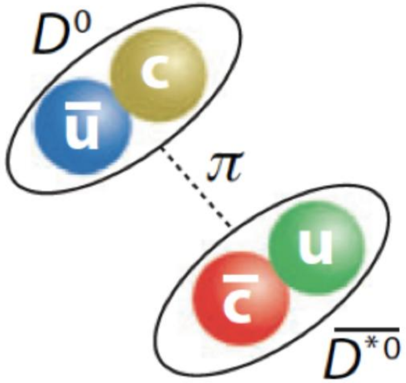
Exotic States and X(3872)

- Hadrons: particles made of quarks and gluons.
  - **mesons** and **baryons**
  - **exotic states**: tetraquarks, pentaquarks, glueballs and hybrids

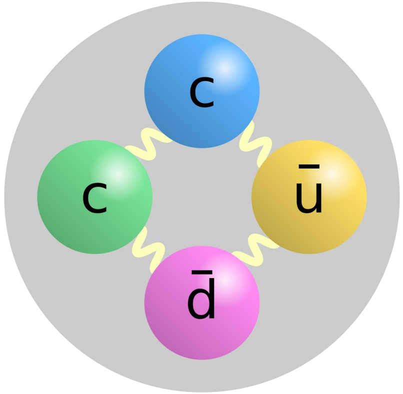
- **X(3872):** the first exotic state discovered in 2003 by the Belle experiment.
  - different explanations for its structure:
    - **charmonium** state
    - D0 and anti-D0* **molecule**
    - **tetraquark**
    - their admixture



charmonium state



molecule

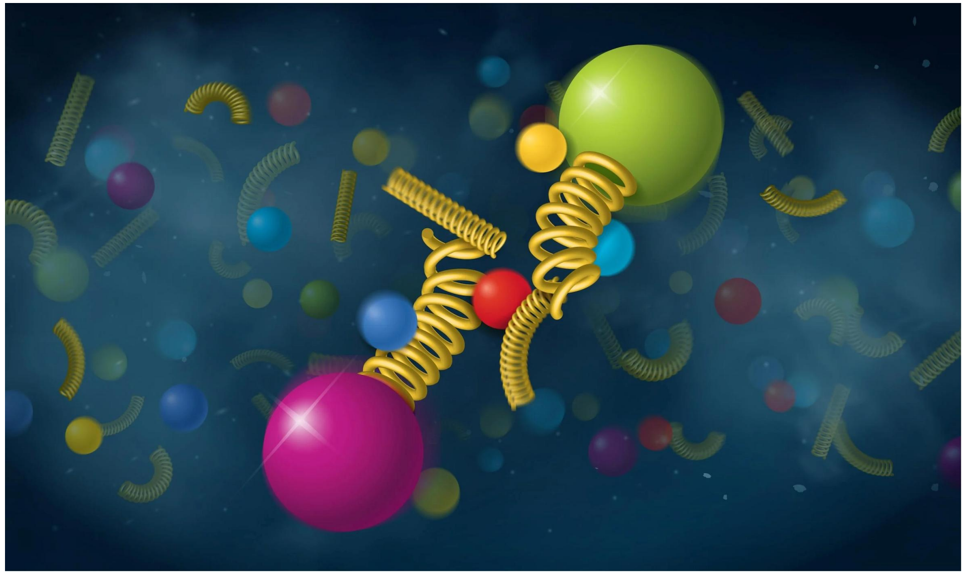


tetraquark

X(3872) as a probe of the QGP

- The interaction between QGP and X(3872)
  - **Coalescence**
    - Coalescence mechanisms could enhance the X(3872) production yield.
  - **Screening**
    - Due to Screening effects, a longer distance between the quarks and antiquarks of X(3872) could lead to a higher dissociation rate.

- **Why** do we want to study the X in HIC?
  - Learn about the nature of X(3872):
    - a compact tetraquark configuration with a radius ~0.3 fm?
    - a molecular state with a radius greater than 1.5 fm?
  - Establish the **first observation** of X(3872) in Pb-Pb collisions
  - Explore the QGP mechanisms



screening effects

Motivation & Strategy

- How to study the interaction between QGP and X(3872)?

For both **pp** and **PbPb**:

- preparation: **data** & **simulation**
- **event selection**: single variable optimization & multi-variable ML
- **efficiency** correction
- **cross section** measurement
- **Nuclear Modification Factor** (RAA) calculation

- Goals for summer project:

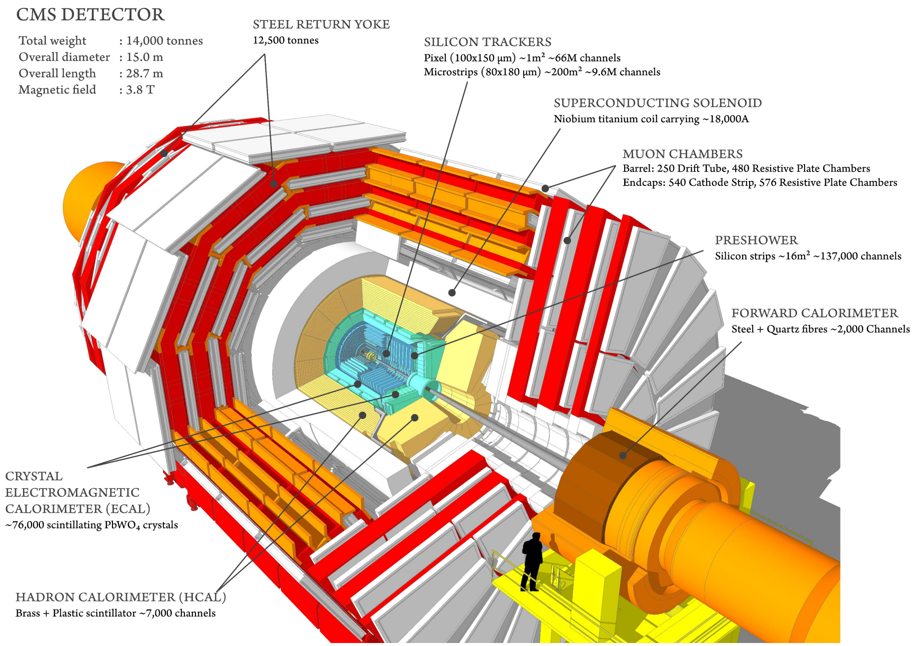
For **pp**

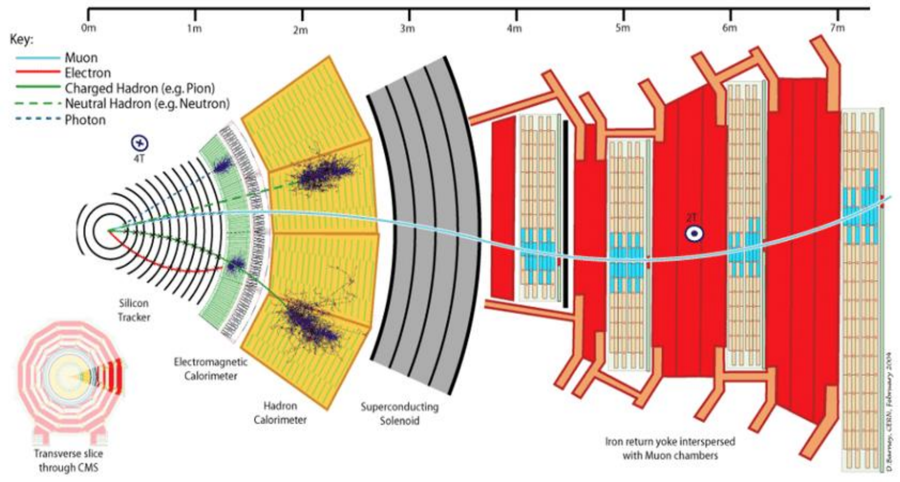
- calculate the ratio of cross sections

Compact Muon Solenoid (CMS)

CMS is a general purpose detector

- It has a cylindrical shape with 15m diameter and 21m in length
- Formed of sub-detector layers; most relevant for this project:
  - muon chambers
  - silicon trackers
- Particles are reconstructed using an algorithm combining the signals provided by the subdetectors
- A trigger system decides in real time whether to record events or to discard them





Data & Simulation

- pp and PbPb data collected by CMS in LHC Run3 ($\sqrt{s} = 5.36 TeV$)
  - **pp: 2024 ($455\mathbf{pb}^{-1}$)** -> in this study
  - PbPb: 2023 ($1.72nb^{-1}$), 2024 ($1.67nb^{-1}$), 2025 (ongoing) -> for future study
- Monte Carlo (MC) simulation
  - simulations done with detector conditions of each year
- Candidate reconstruction
  - select pairs of muons ($\mu^+\mu^-$) and pairs of tracks ($\pi^+\pi^-$) originating from a common point

Muon & Track Selection

Muons

- **Soft muons:**
  - **normalized $\chi^2 \leq 1.8$**
  - **Hits:**
    - tracker layers ≥ 6
    - pixel Layers ≥ 1
  - **Displacement from vertex:**
    - $dz < 35$ cm
    - $dxy < 4$ cm

- **Acceptance region:**
  - $p_T \geq 3.5 GeV$ & $|\eta| < 1.2$
  - $p_T \geq (5.47 - 1.89 \times |\eta|)\ GeV$ & $1.2 \leq |\eta| < 2.1$
  - $p_T \geq 1.5 GeV$ & $|\eta| < 2.4$

- **HLT matching:**
  - **Path:** "*HLT_PPRefL1DoubleMu0_v6*"
  - **Filter:** "*hltL1fL1sDoubleMu0L1Filtered0PPRef*"

Tracks

- **Quality:**
  - High purity tracks
  - $\sigma_{p_T} / p_T < 0.1$
  - N_{hits} (pixel + tracker hits) ≥ 11
  - $\frac{\chi^2}{ndf} / N_{hits} < 0.18$

- **Acceptance:**
  - $p_T > 0.5 GeV$
  - $|\eta| < 2.4$

Candidates

- **Fiducial region:**
  - $p_T > 5 GeV$
  - $|y| < 2.4$

Di-muon system

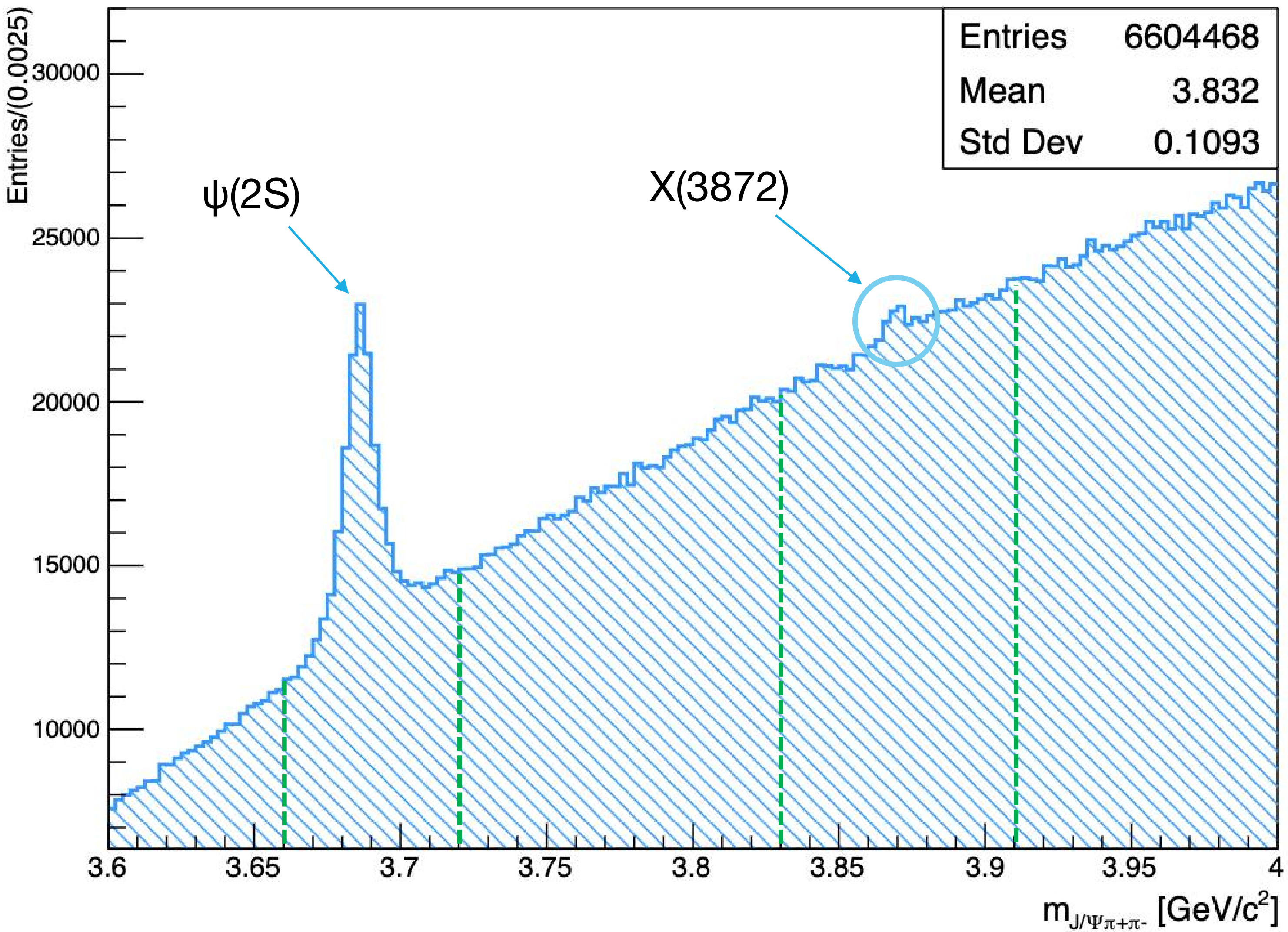
- Opposite muon charges
- Common vertex probability > 1%
- System's mass within 0.15 GeV from J/Ψ mass

X(3872) & ψ(2S)

Decay channels:

- X(3872) ⟶ J/ψ + ρ ⟶ $\mu^+ + \mu^- + \pi^+ + \pi^-$
- X(3872) ⟶ J/ψ + $\pi^+ + \pi^-$ ⟶ $\mu^+ + \mu^- + \pi^+ + \pi^-$
- Ψ(2S) ⟶ J/ψ + $\pi^+ + \pi^-$ ⟶ $\mu^+ + \mu^- + \pi^+ + \pi^-$

Sideband region is defined as [3.6,3.66] && [3.72,3.83] && [3.91,4.0] GeV



Mass Spectrum of Ψ(2S) and X(3872) before applying any selection cuts, only preselection cuts applied

Variables for X(3872) selection

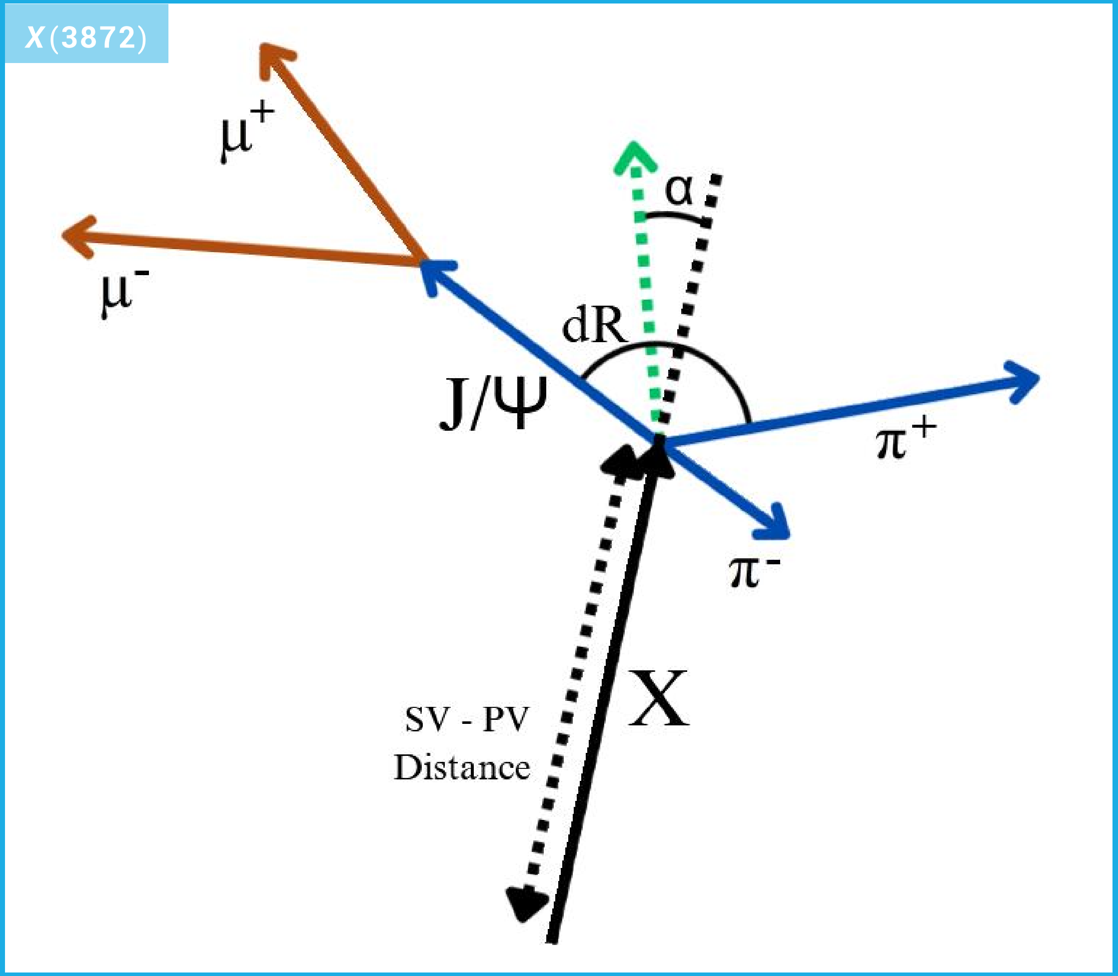
Normalized Flight Length: 3D distance between the primary vertex and the secondary vertex where X(3872) is formed, normalized by its uncertainty

Normalized Flight Length in 2D: distance in the transverse plane between the primary vertex and secondary vertex, normalized by its uncertainty

Pointing Angle (α): opening angle between the PV -> SV flight vector and the reconstructed X(3872) candidate momentum

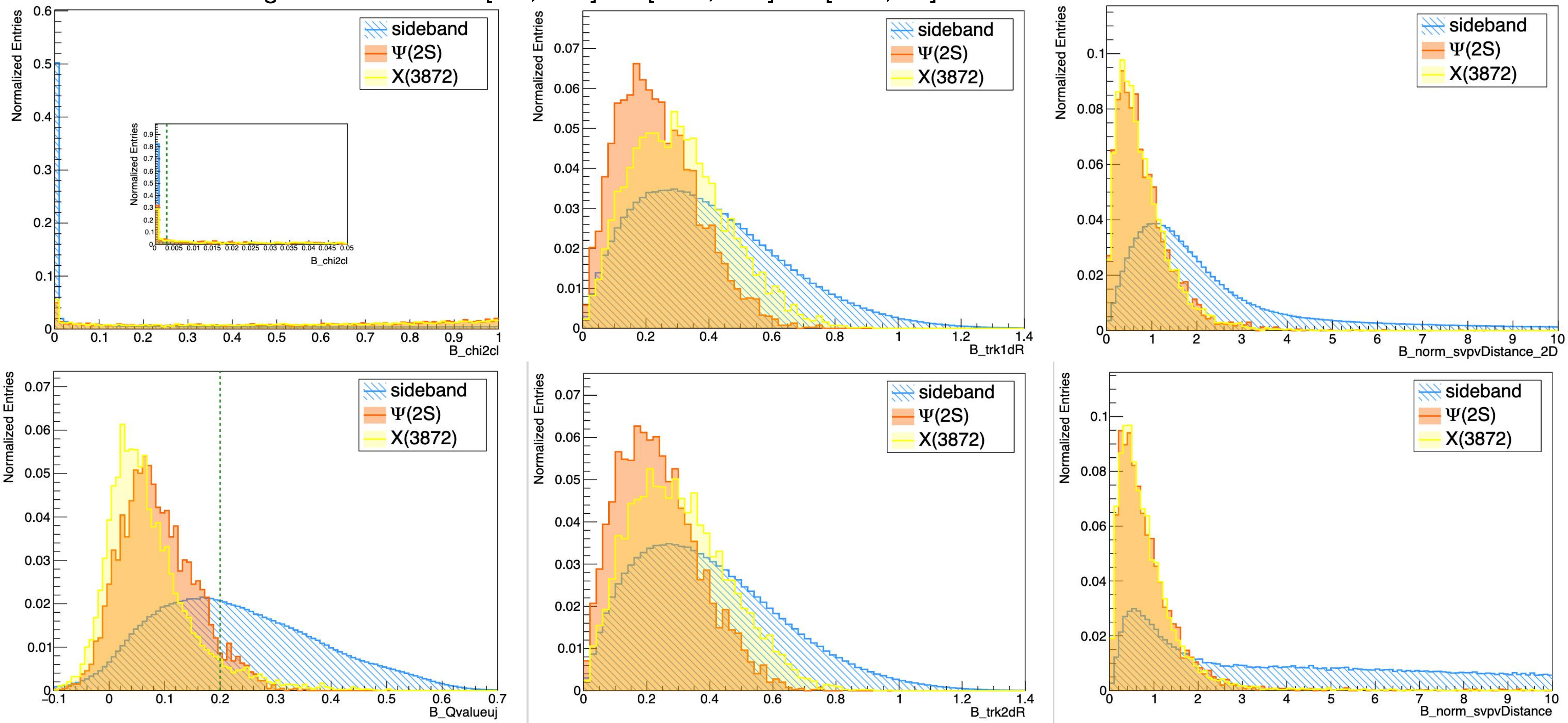
Projected Pointing Angle (θ): opening angle between the reconstructed X(3872) momentum and the PV -> SV vector projected onto the transverse plane (xy)

dR: angular distance between each pion track and J/ψ



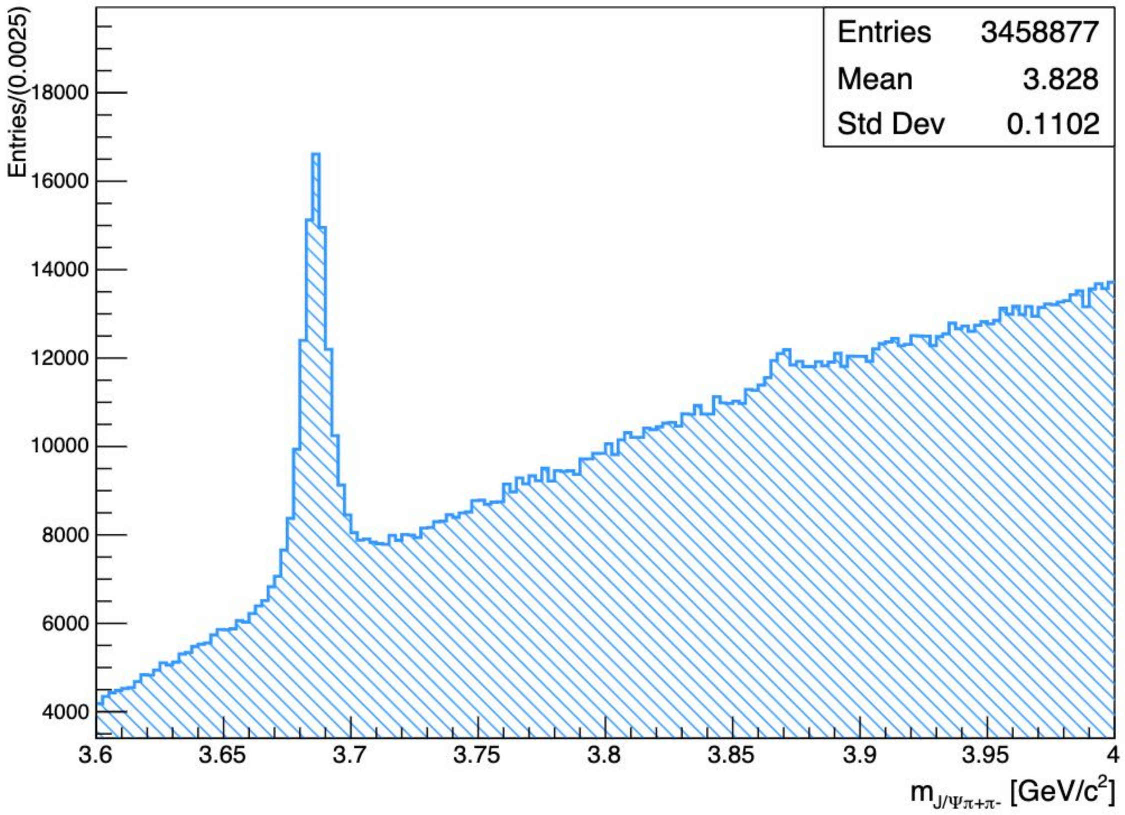
Variable distributions for Signal and Background

- sideband region is defined as [3.6,3.66] && [3.72,3.83] && [3.91,4.0] GeV

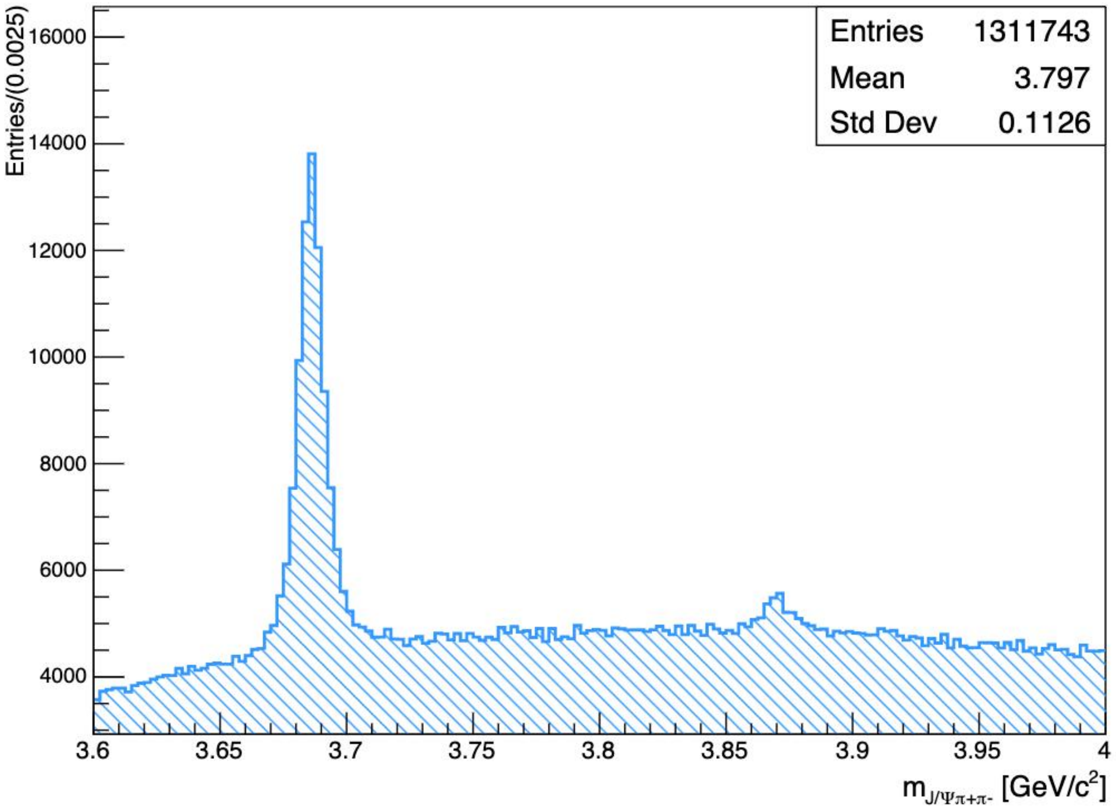


Pre-selection cuts

- pre-cut1: B_chi2cl > 0.003



- pre-cut2: B_Qvalueuj < 0.2 && pre-cut1



Optimization

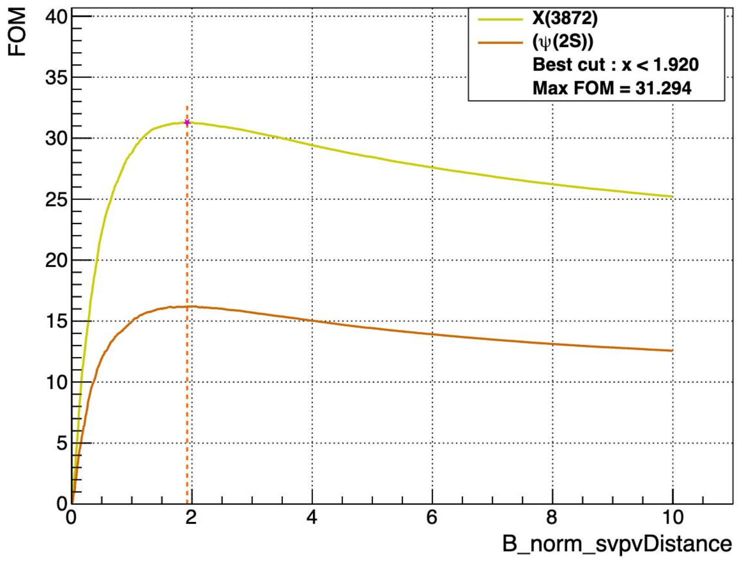
- **Goal** : discriminate signal from background

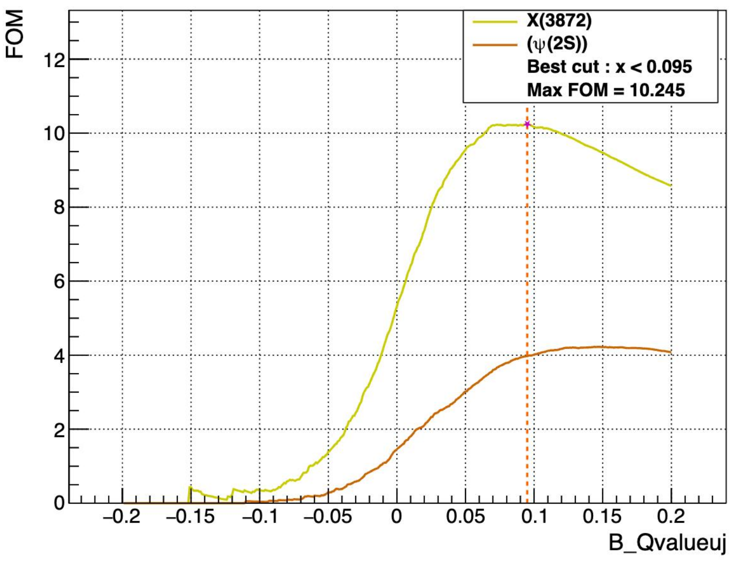
- **Method** : compare the performance and figure of merit (FOM) from different cuts
  - FOM is calculated for ψ(2S) and X(3872) **separately**.
  - The max FOM of **X(3872)** is considered as **"best cut"**.

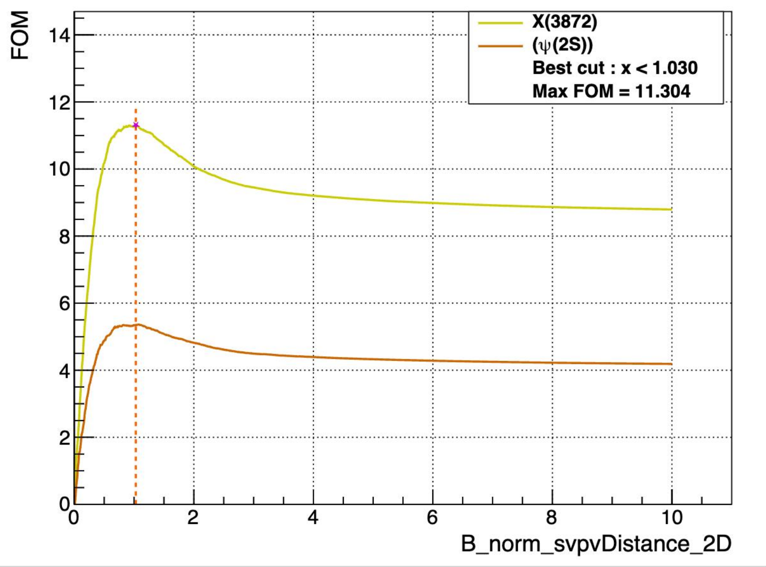
$$FOM = \frac{f_S \times S_{MC}}{\sqrt{f_S \times S_{MC} + f_B \times B}}$$

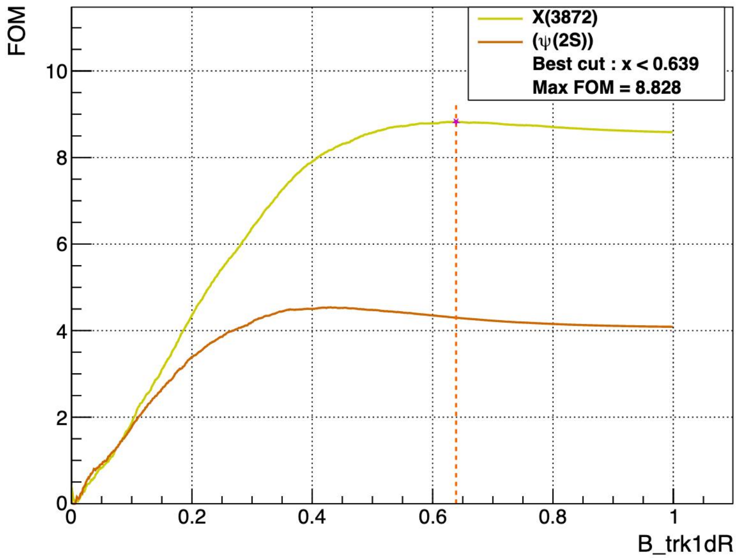
$$f_S = \frac{S_{data}}{S_{MC}} \qquad f_B = \frac{B(signal\ region)}{B(sideband\ region)}$$

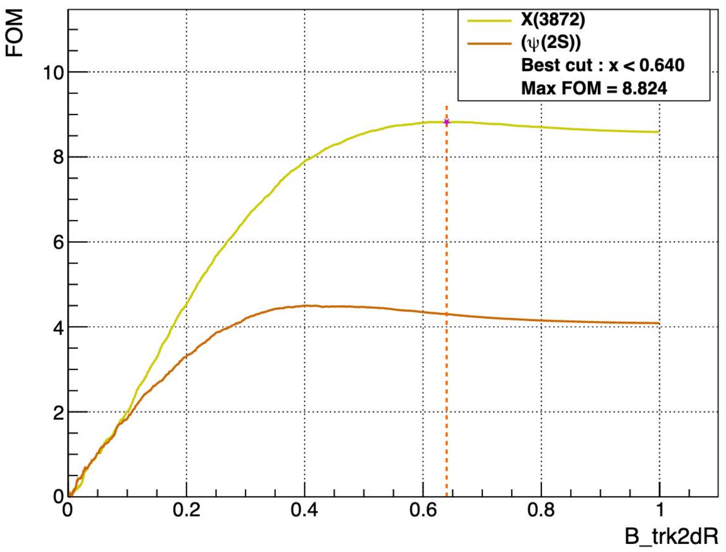
Optimization of Different Variables





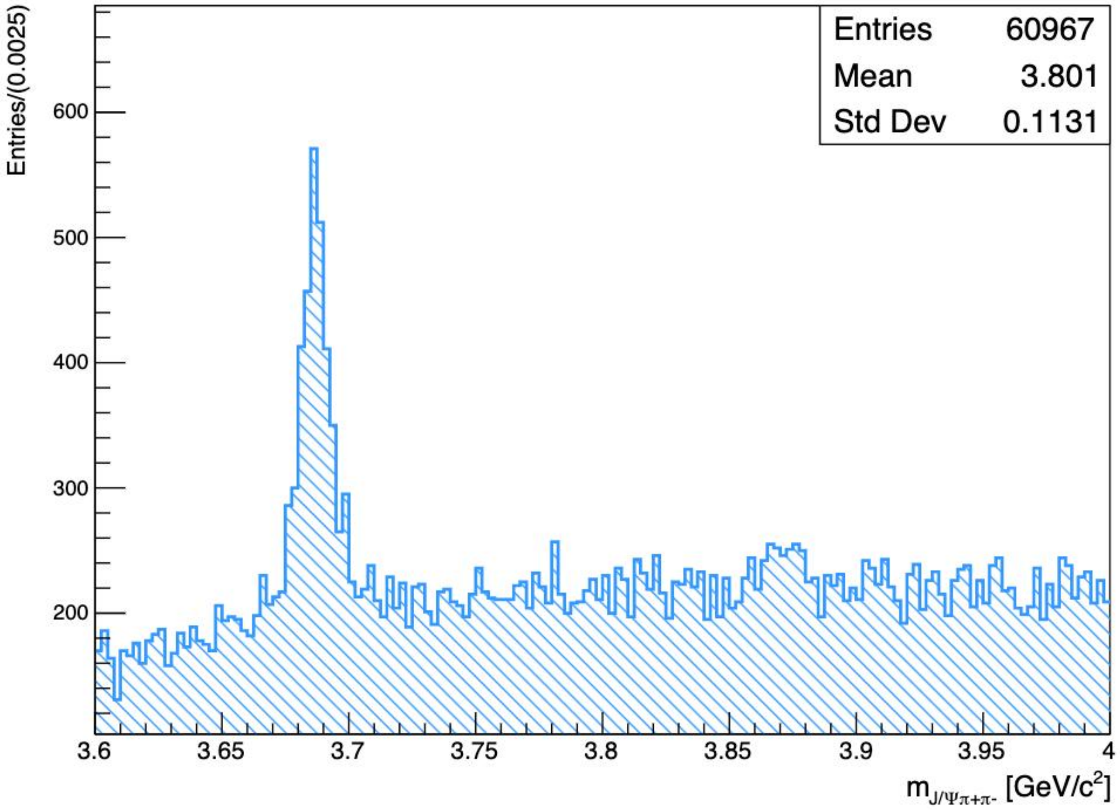




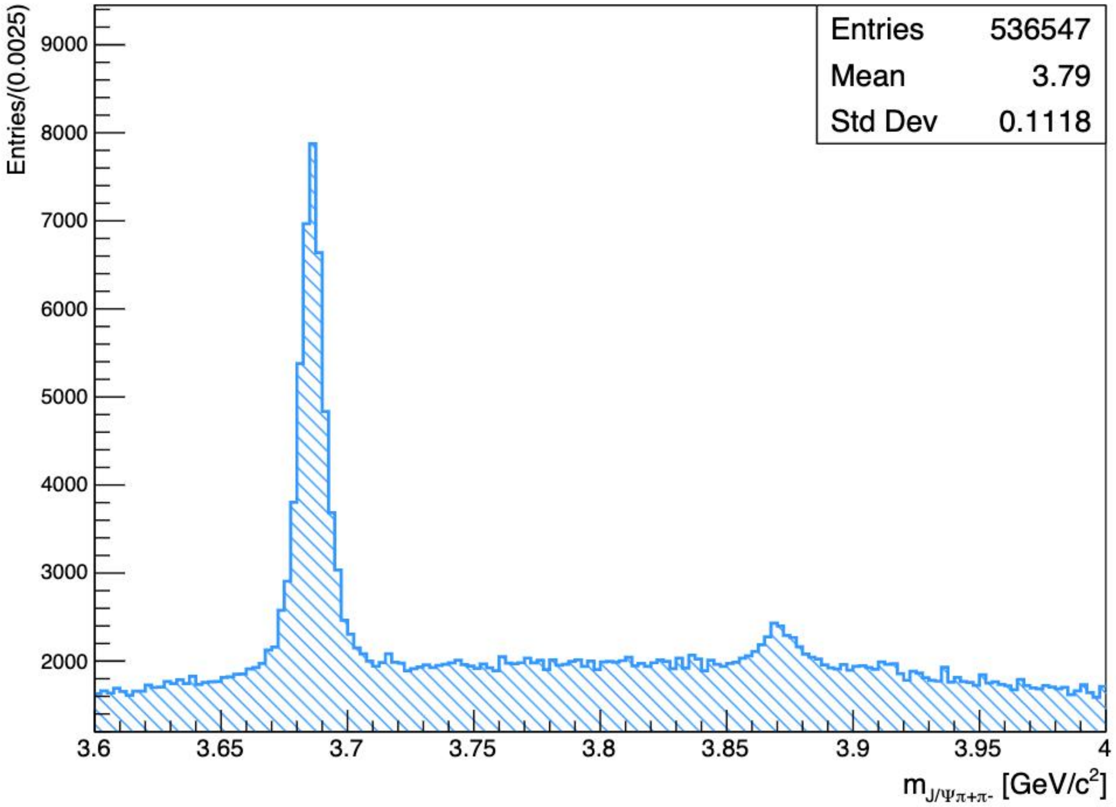


Mass Distribution after Optimal Cuts

- optimal cut1: B_norm_svpvDistance < 1.92

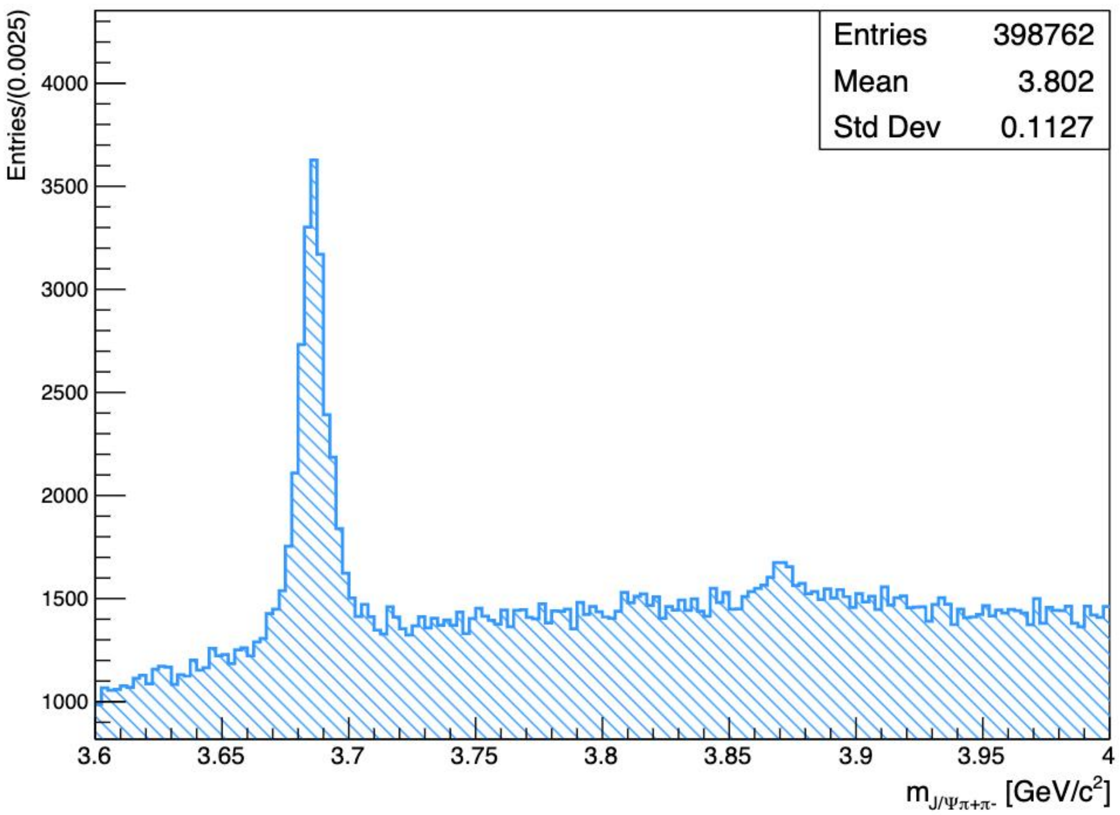


- optimal cut2: B_Qvalueuj < 0.095

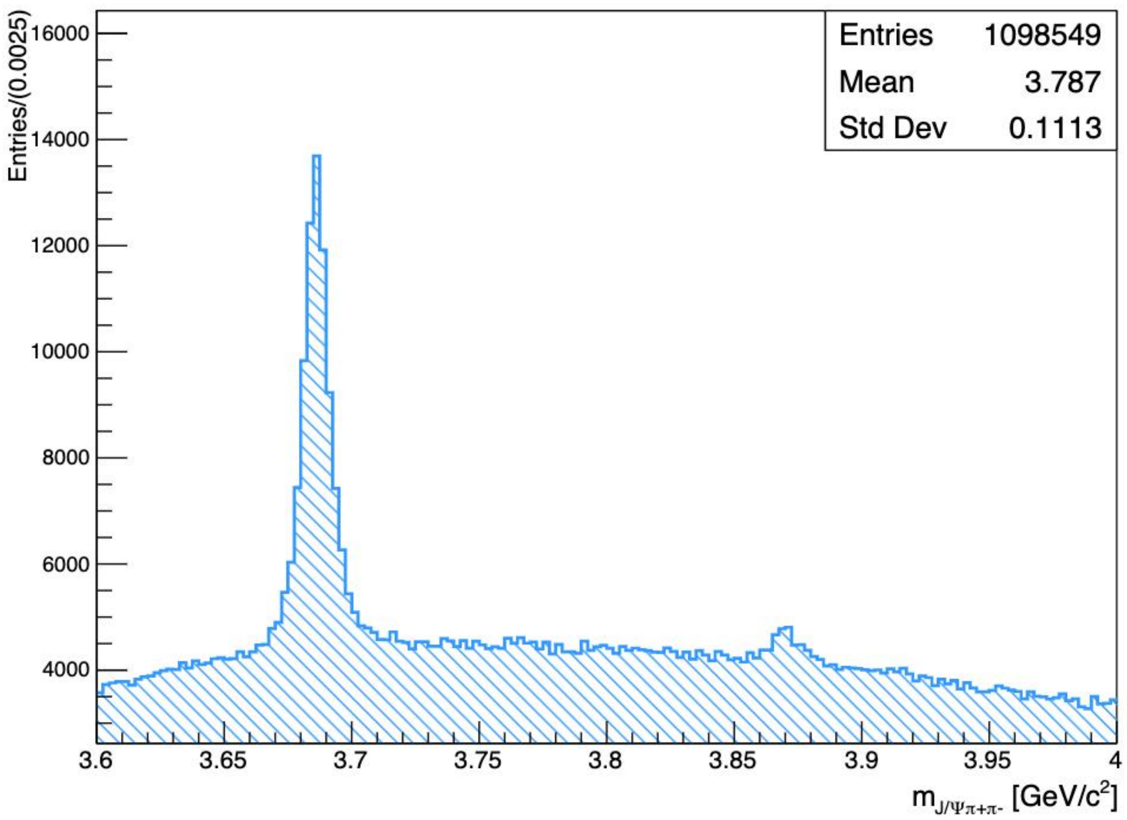


Mass Distribution after Optimal Cuts

- optimal cut3: B_norm_svpvDistance_2D < 1.030

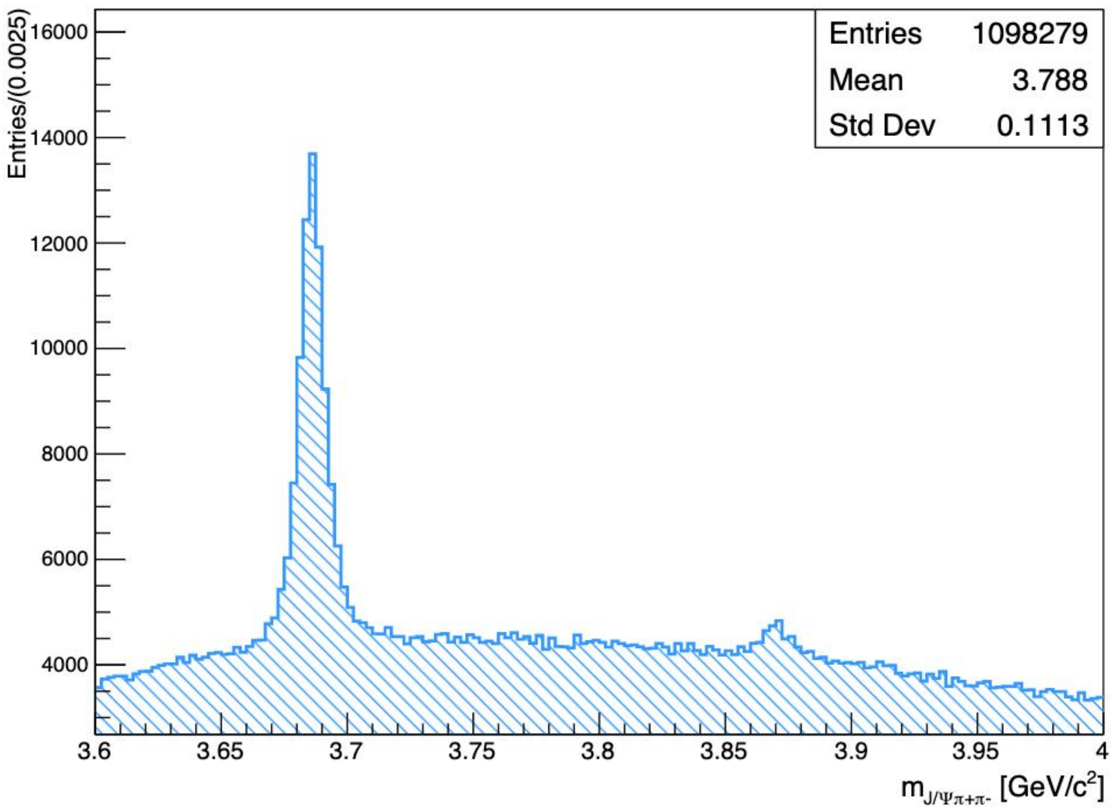


- optimal cut4: B_trk1dR<0.639

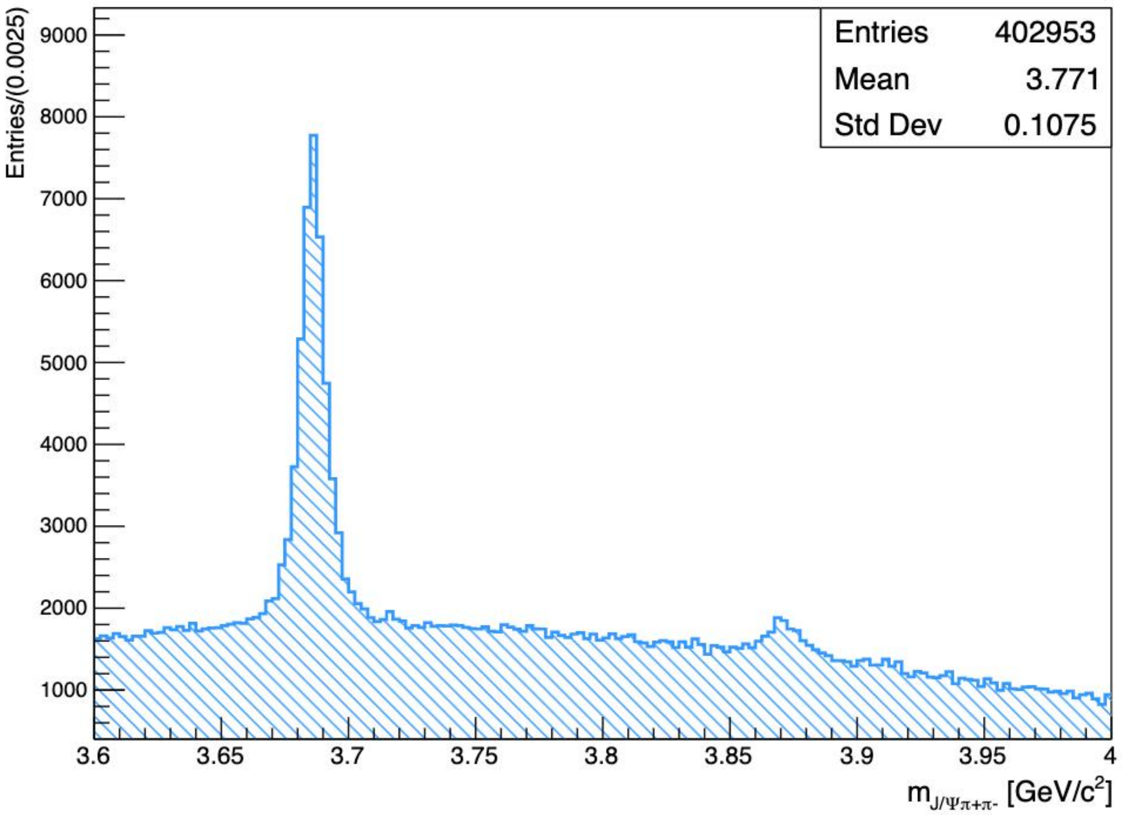


Mass Distribution after Optimal Cuts

- optimal cut5: B_trk2dR<0.64



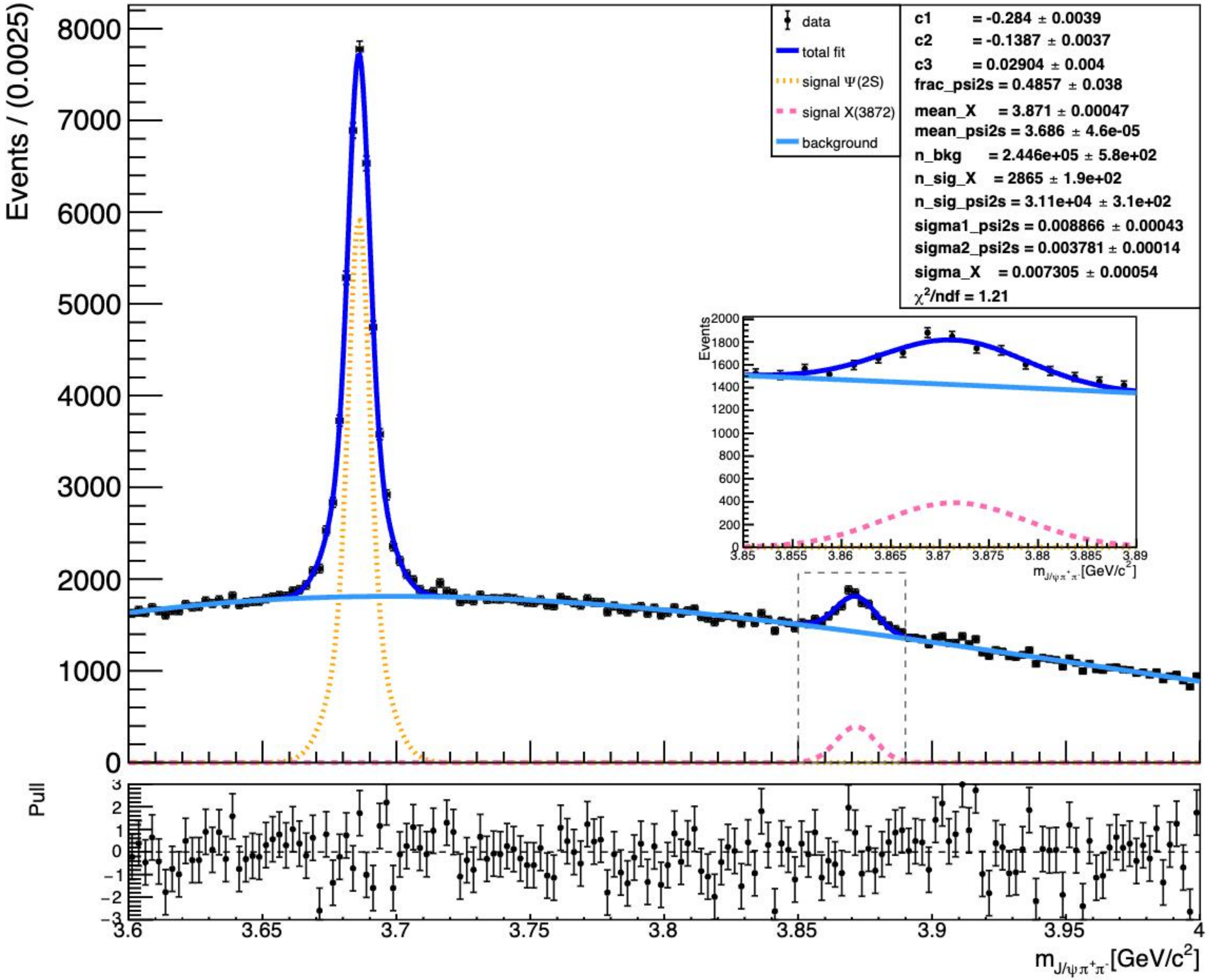
- **optimal cuts**: optimal cut2 && cut4 && cut5
- B_Qvalueuj < 0.095 && B_trk1dR<0.639 && B_trk2dR<0.64



Fitting Method

- ψ(2S) : double gaussian
- X(3872) : single gaussian
- background : 3rd order Chebychev polynomial

- $N(X(3872)) = (2.87 \pm 0.19) \times 10^3$
- $N(\psi(2S)) = (3.11 \pm 0.03) \times 10^4$



$m_{J/\psi\pi^+\pi^-}$ fit result

Cross Section

$$A = \frac{N(Acc\ cuts)}{N(GEN)}$$

$$\epsilon = \frac{N(All\ cuts)}{N(Acc\ cuts)}$$

$$\sigma = \frac{N}{A \times \epsilon \times BR \times L}$$

- N : Yield of signal <- Fit
- A : acceptance <- MC
- ϵ : efficiency <- MC
- BR : branching fraction <- PDG
- L : luminosity <- CMS

Ratio of
Cross Section times Branching Fraction

$$R = \frac{\sigma(pp \to X(3872) + anything) \times BR(X(3872) \to J/\psi\pi^+\pi^-)}{\sigma(pp \to \psi(2S) + anything) \times BR(\psi(2S) \to J/\psi\pi^+\pi^-)}$$

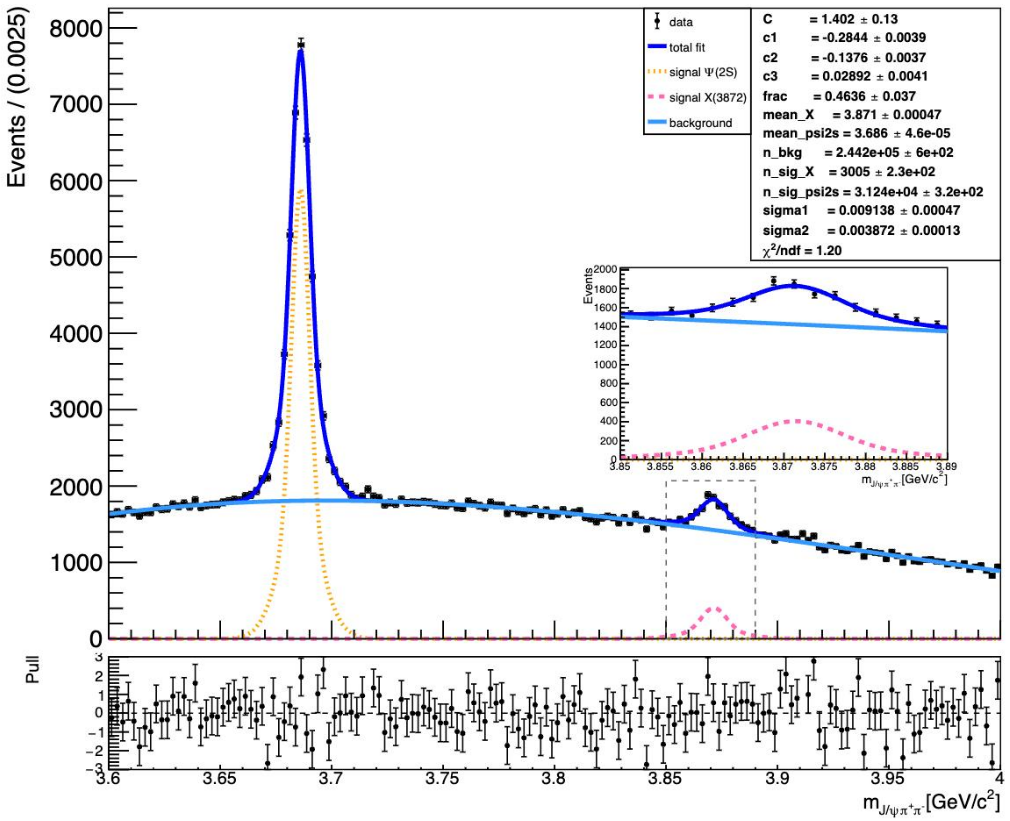
$$R = \frac{N_{X(3872)} \times A_{\psi(2S)} \times \epsilon_{\psi(2S)}}{N_{\psi(2S)} \times A_{X(3872)} \times \epsilon_{X(3872)}}$$

- $BR(X(3872) \to J/\psi\pi^+\pi^-)$ has large uncertainties according to PDG[1]
- a previous study based on CMS Run1 data calculated this ratio

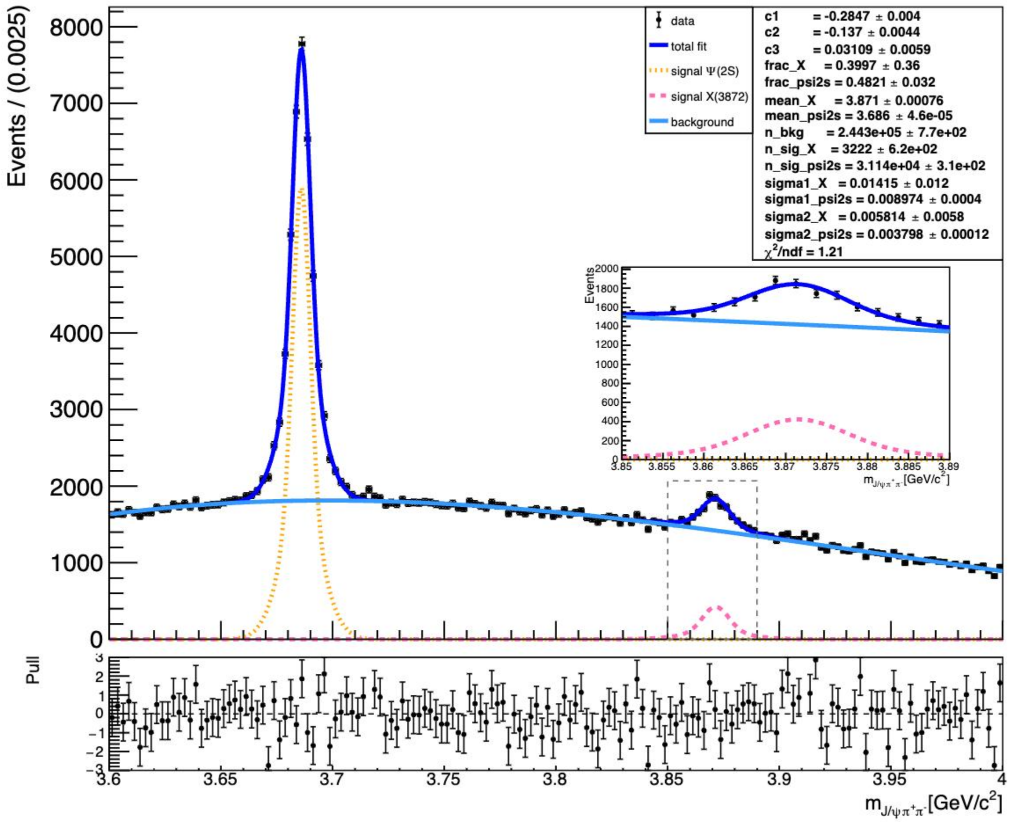
[1]S. Navas et al. (Particle Data Group), Phys. Rev. D 110, 030001 (2024)

Systematic Uncertainties from Fitting

- Method1
  - ψ(2S) : double gaussian (σ_1, σ_2)
  - X(3872) : double gaussian ($C\sigma_1, C\sigma_2$)
  - background : 3rd order Chebychev polynomial

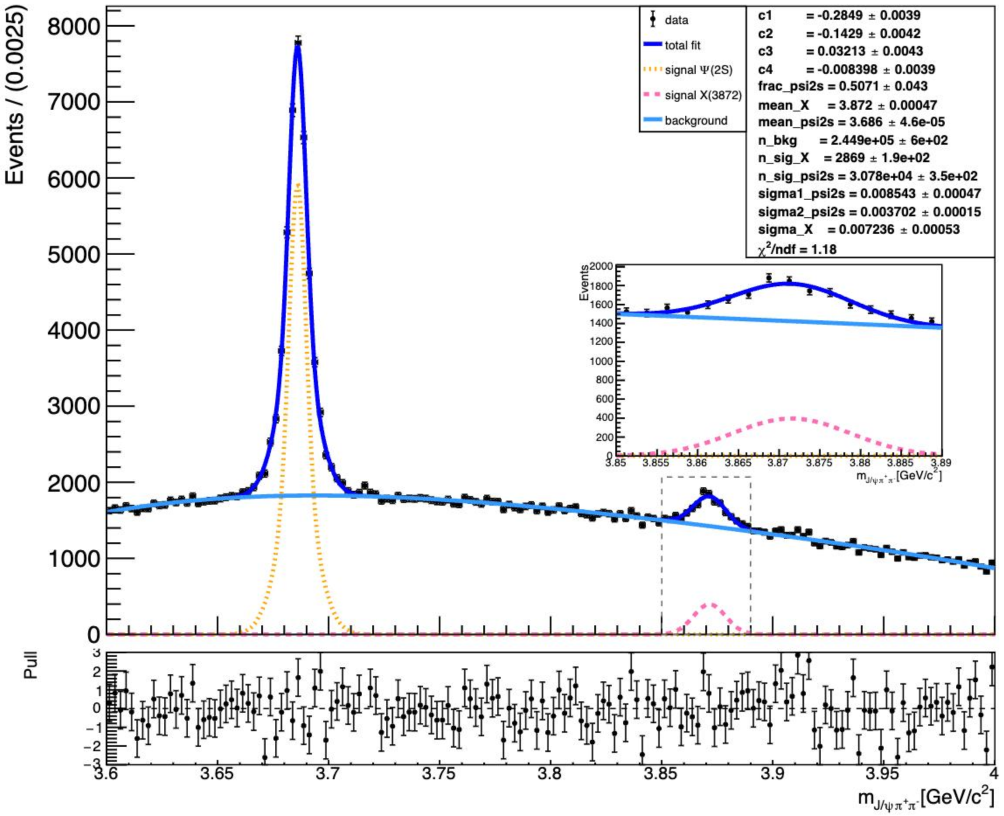


- Method2
  - ψ(2S) : double gaussian
  - X(3872) : double gaussian
  - background : 3rd order Chebychev polynomial



Systematic Uncertainties from Fitting

- Method3
  - ψ(2S) : double gaussian
  - X(3872) : single gaussian
  - background : 4th order Chebychev polynomial



- Total systematic uncertainties from fitting are the quadrature sum of the maximum uncertainties of signal and background model variations

Statistic & Systematic Uncertainties

- Systematic uncertainties from alternative fitting methods
- Statistic uncertainties from fitted data

Table1 : Systematic Uncertainties

	$\psi(2S)$	$X(3872)$
Method1	0.46%	4.89%
Method2	0.09%	14.5%
Method3	1.02%	0.15%
Total	1.12%	14.5%

Table2 : Statistic Uncertainties

	$\psi(2S)$	$X(3872)$
Fitting	1.01%	6.70%

Result & Comparison

The **result of this study**

- pp collisions at $\sqrt{s} = 5.36 TeV$ (CMS Run 3 pp)
- Fiducial region: $p_T > 5 GeV, |y| < 2.4$

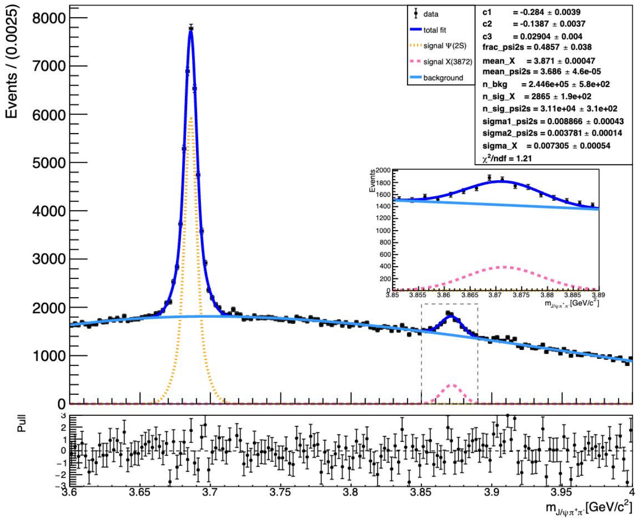
$$R = (7.60 \pm 0.52(stat.) \pm 1.10(syst.)) \times 10^{-2}$$

in **comparison** with the **result of previous study**

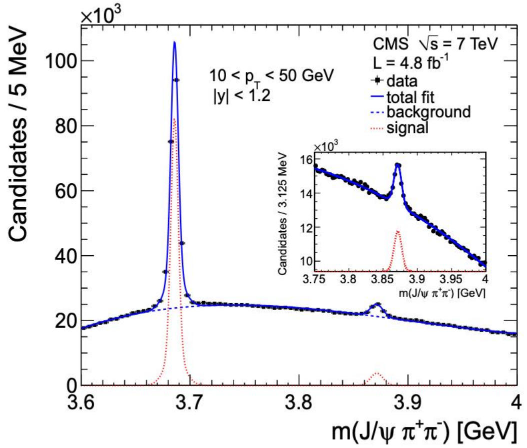
- pp collisions at $\sqrt{s} = 7 TeV$ (CMS Run I)[1]
- Fiducial region: $10 GeV < p_T < 50 GeV, |y| < 2.4$

$$R = (6.56 \pm 0.29(stat.) \pm 0.65(syst.)) \times 10^{-2}$$

The results are **consistent within uncertainties**, providing a certain degree of validation for this study



$m_{J/\psi\pi^+\pi^-}$ fit results of this study



$m_{J/\psi\pi^+\pi^-}$ fit results of previuos study[1]

Summary & Outlook

The study is based on CMS Run3 pp data($\sqrt{s} = 5.36 TeV$)

- Selection study for X(3872), ψ(2S)
- Different fitting methods
- Measurement of cross sectio ratio
- Statistic & Systematic uncertainties

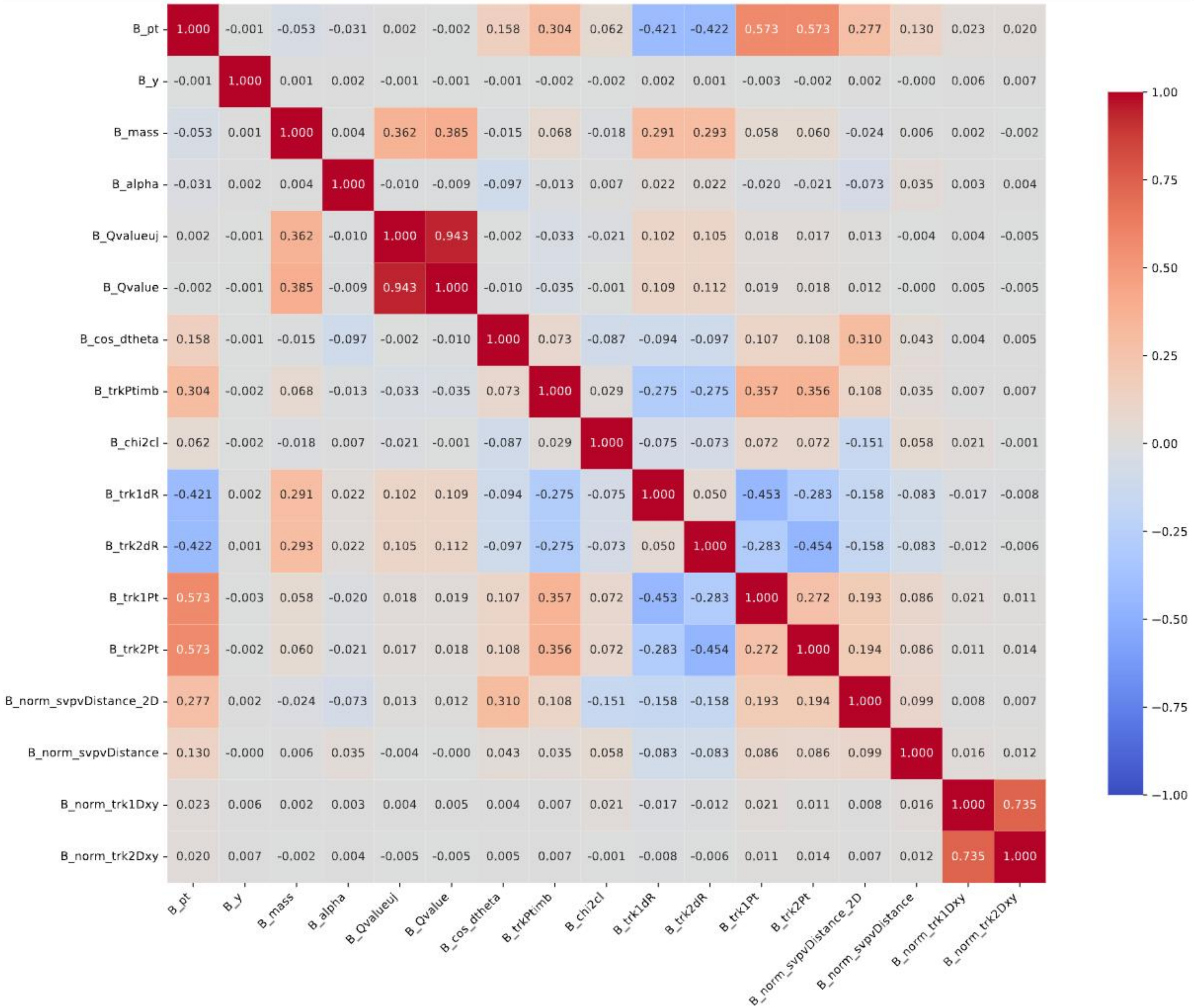
In the future

- MC validation
- ML tools for multi-variable selection
- More complete uncertainties study
- PbPb dataset analysis

BACKUP

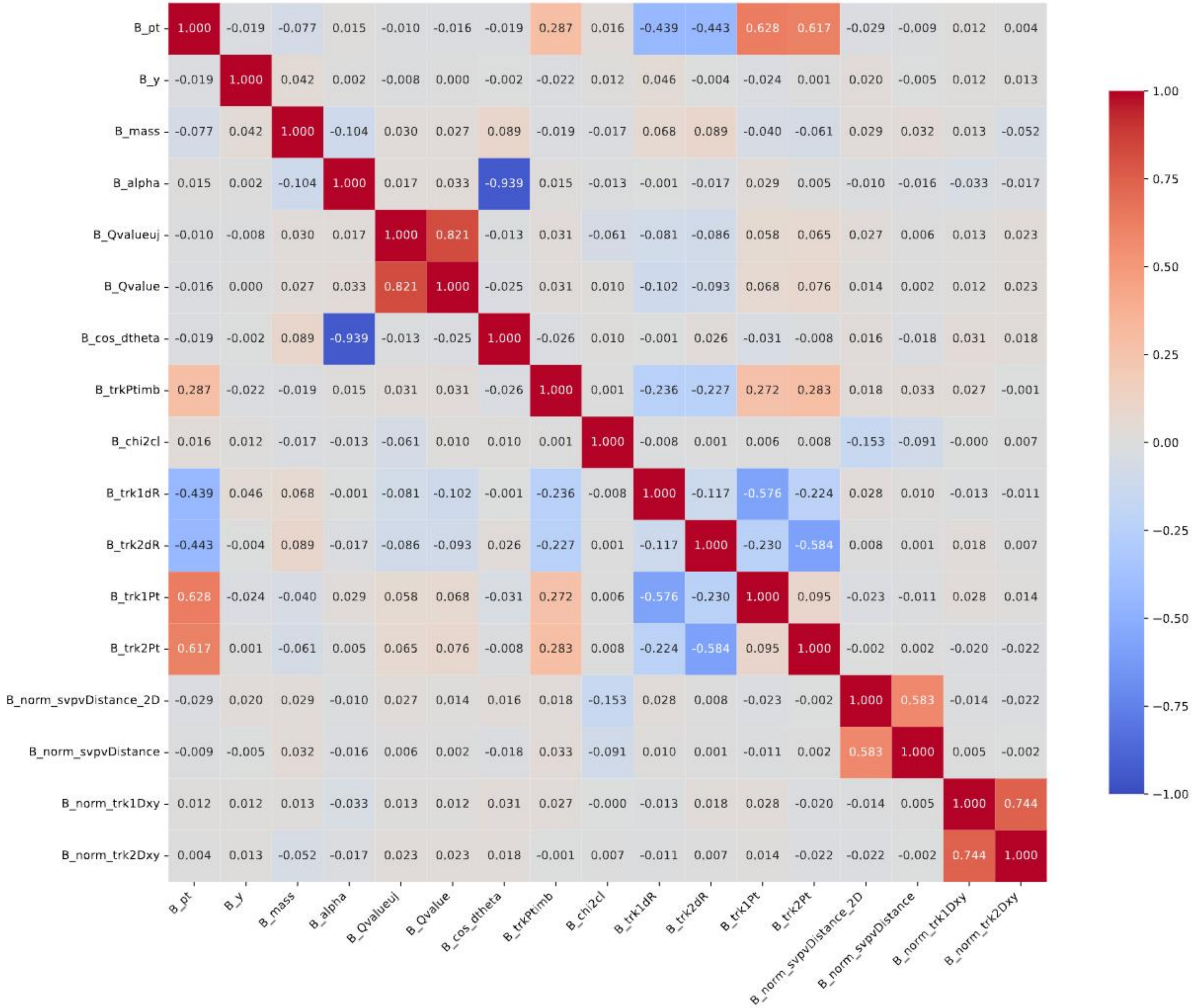
Correlation Matrix

- sideband region is defined as [3.6,3.66] && [3.72,3.83] && [3.91,4.0] GeV



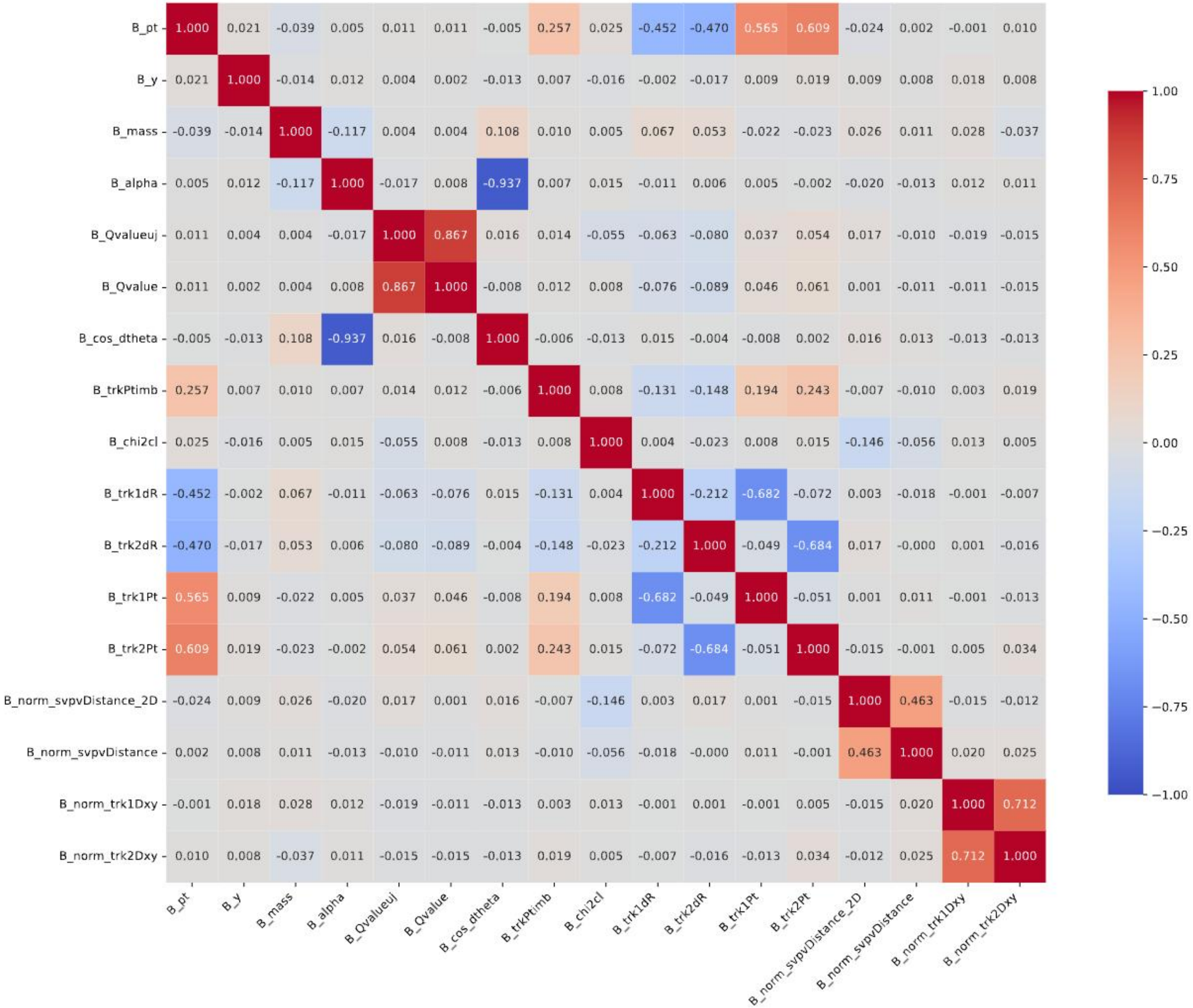
Correlation Matrix of different variables from the sideband data

Correlation Matrix



Correlation Matrix of different variables from ψ(2S) MC

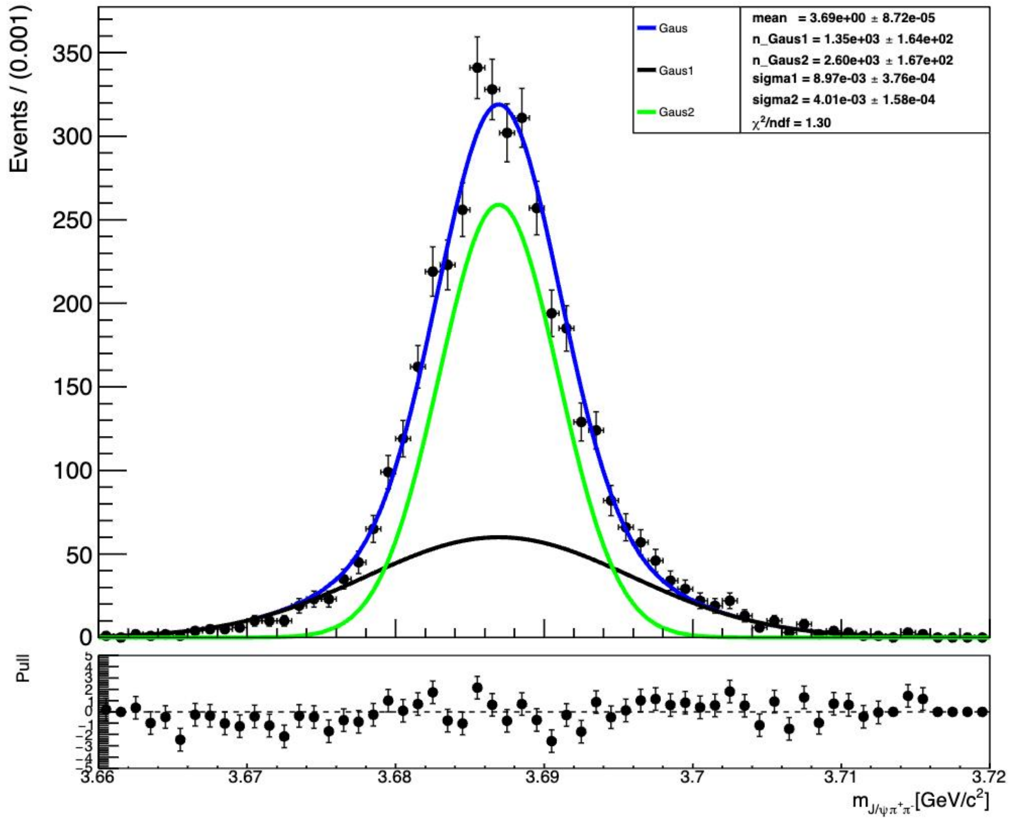
Correlation Matrix



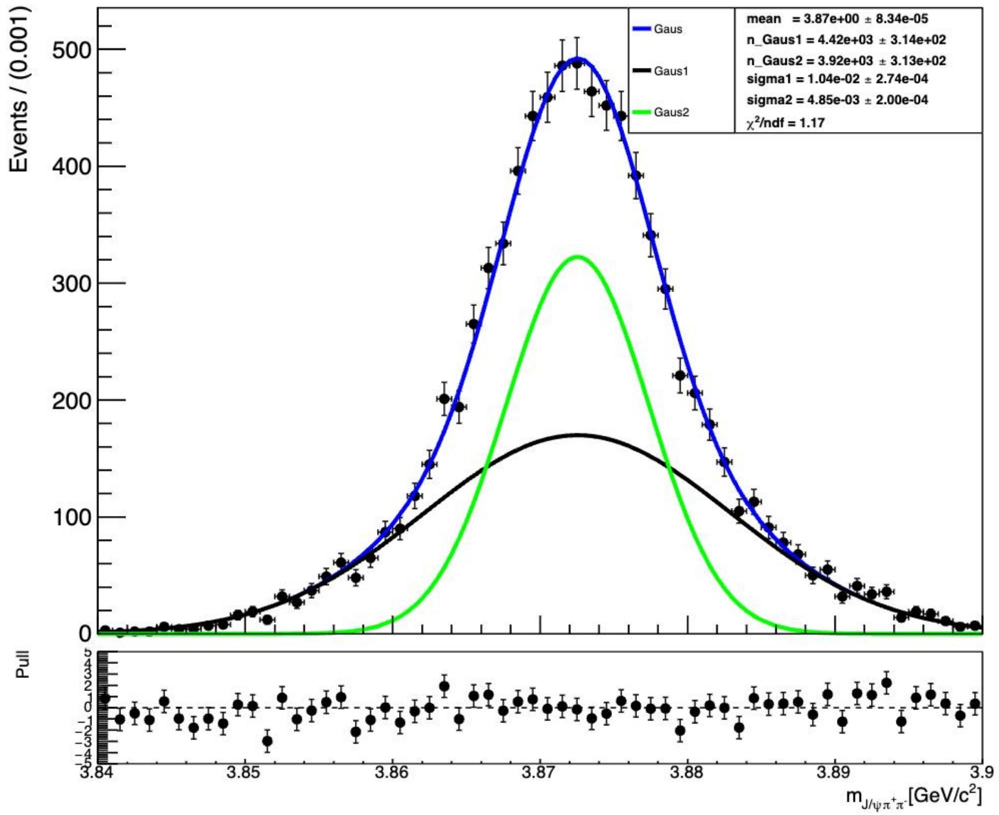
Correlation Matrix of different variables
from X(3872) MC

Fit MC

- $\sigma_{eff} = 6.17 \times 10^{-3}$
- sideband region [3.6,3.66] && [3.72,3.83] is out of mean $\pm\, 4\sigma_{eff}$ region

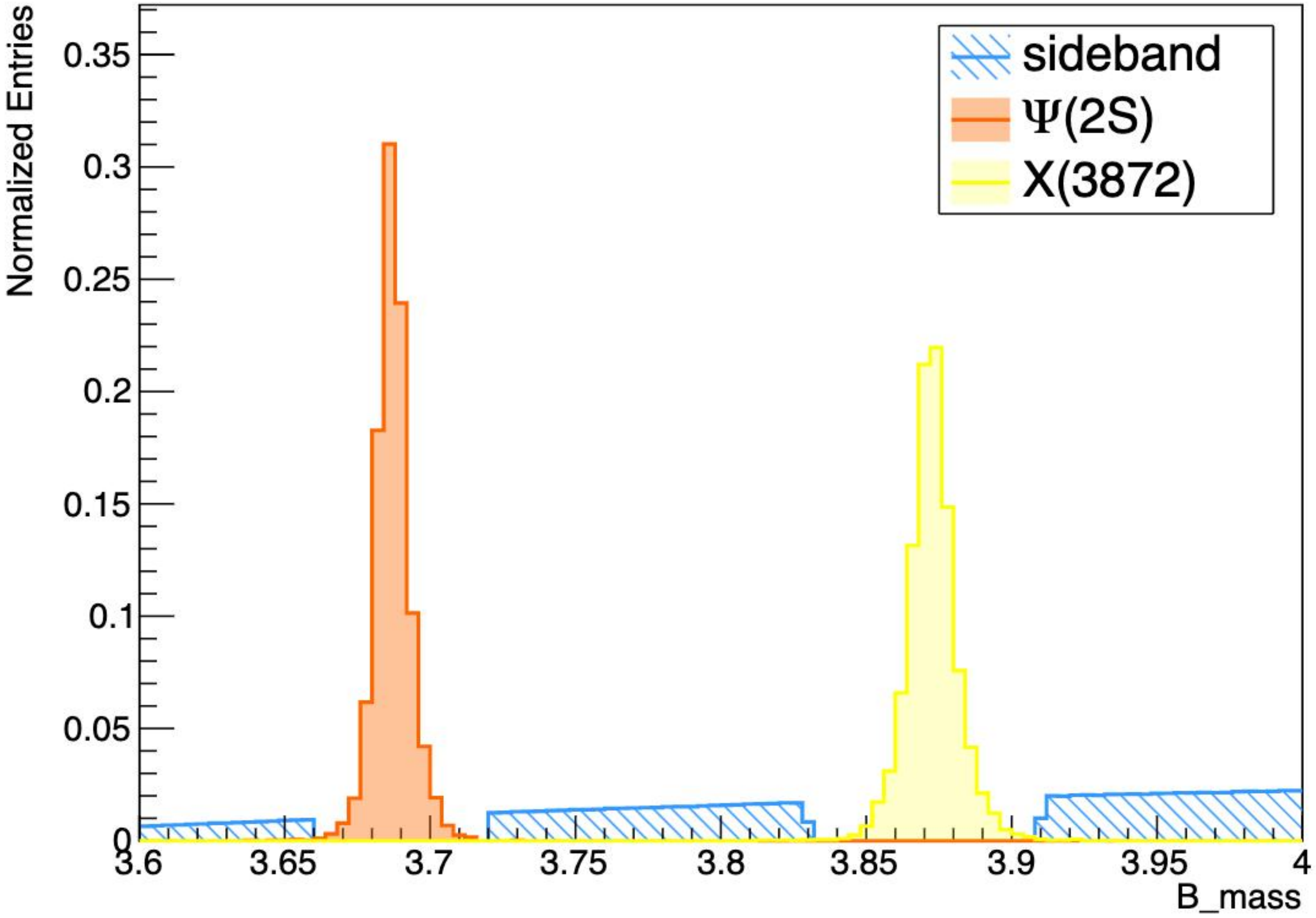


- $\sigma_{eff} = 8.27 \times 10^{-3}$
- sideband region [3.72,3.83] && [3.91,4.0] is out of mean $\pm\, 4\sigma_{eff}$ region



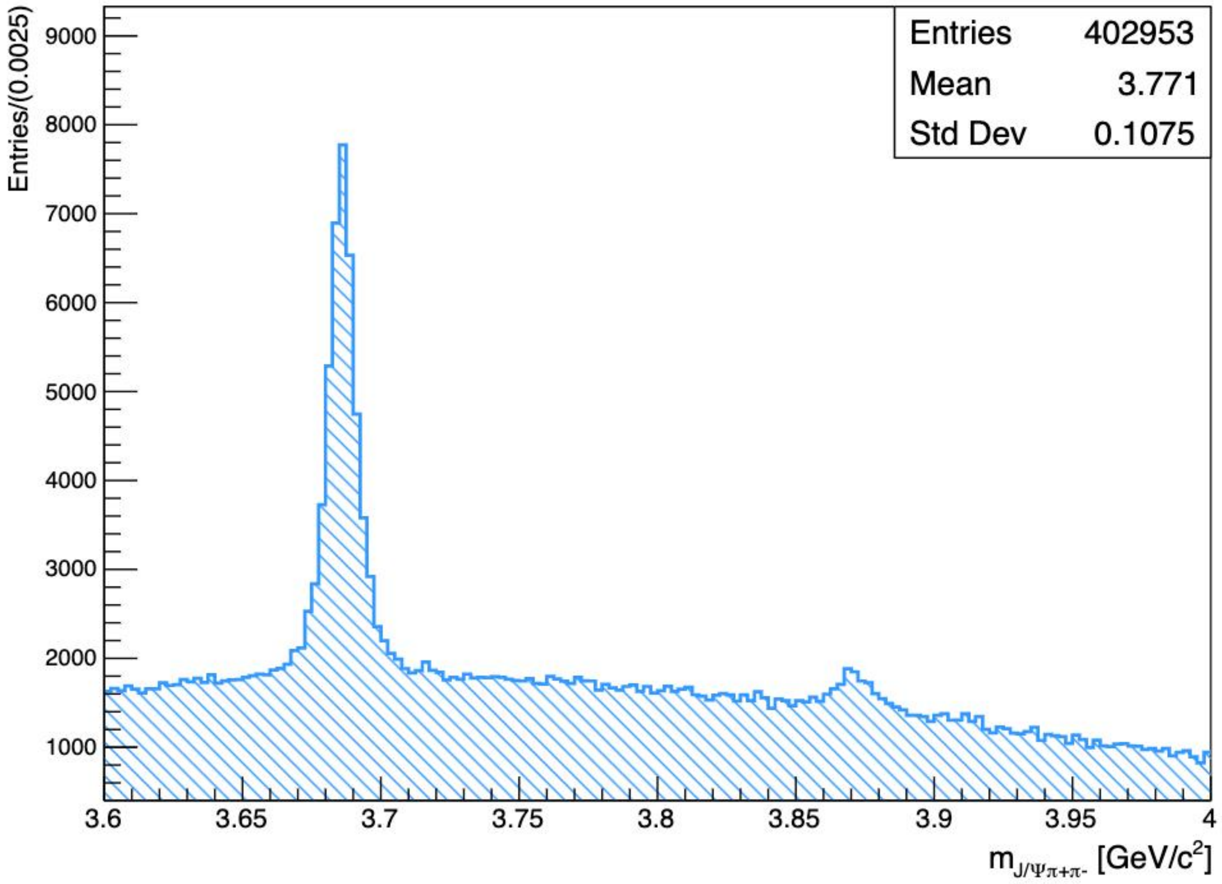
Sideband Region

- sideband region is [3.6,3.66] && [3.72,3.83] && [3.91,4.0] GeV



Performance of Optimal Cuts

- **optimal cuts**: optimal cut2 && cut4 && cut5
- B_Qvalueuj < 0.095 && B_trk1dR<0.639 && B_trk2dR<0.64



$m_{J/\psi\,\pi^+\pi^-}$ distribution after optimal cuts